



The impact of key parameters on the cycle efficiency of multi-stage RCAES system

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Abstract Due to the uncertainty and anti-peaking nature, large scale integration of renewable energy imposes great challenges to the operation and dispatch of power systems. Compressed air energy storage (CAES) system provides new ideas to solve this problem as its characteristics of fast regulating, flexible location and long-service life. Especially, regenerative compressed air energy storage (RCAES) system is widely concerned as its capability of heat recovery in the compression process. The cycle efficiency is a key indicator of RCAES system which can be significantly impacted by the key parameters of the systems including compression ratio, exhaust air pressure of throttle (EAPT) and the maximum working pressure (MWP) of compressed air storage vessel (CASV). However, current research mostly focuses on the thermodynamic process and few studies have focused on the impact of key parameters on RCAES system. Based on the efficiency evaluation method which was formulated through the electrical-mechanical-thermal dynamic process and measurable parameters, the impact of key parameters on the cycle efficiency of RCAES system is analyzed in this paper and a practical RCAES design scheme is adopted for case study.

Keywords RCAES, Efficiency evaluation, Parameters analysis, Energy conversion, Energy storage

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1 Introduction

Integration of large-scale renewable energy has imposed great challenges on power system operation due to its uncertainty and anti-peaking nature. The load regulating capacity was seriously deficient in Gansu power grid with 5.409 GW integration of wind power by the end of 2011 [1]. In order to effectively cope with the uncertainty and anti-peaking nature of renewable energy, viable option includes the innovative schedule strategy to optimize system reserves, Energy Storage System (ESS) and so on [2–7].

Chemical battery, pumped hydro, flying wheel, superconducting and compressed air are main patterns of energy storage currently. Chemical battery is the most mature one but with high cost and environmental risk. Pumped hydro energy storage is widely applied in power systems. However, its location depends on the geographical environment. Large-scale applications of flying wheel or superconducting energy storage are very limited in power system practically [8]. Compressed air energy storage (CAES) system is widely concerned in recent years due to its characteristics of high-capacity, long-service life and flexible location of which Huntorf in Germany and McIntosh in USA are representative systems globally [9].

Most existing CAES systems are with combustion process which could improve the cycle efficiency with compressed air. However, such CAES system relies greatly on natural gas supply [10]. To overcome the above disadvantages, regenerative compressed air energy storage (RCAES) system is concerned in energy storage area both in science and engineering due to its capability of reusing compression heat in expansion process. The RCAES system can conspicuously improve the system efficiency without any greenhouse gases emission. The expected efficiency of the typical advanced adiabatic compressed air energy storage system can be regarded as a kind of RCAES

system under construction by RWE in Germany is 70 % [11–13].

The technology project “Research of Key Technology and Engineering Application of Compressed Air Storage” (simply as RCAES project) in China is started in 2012. One of the key technologies to be concerned in the project is how to reuse the heat released in the compression process with high efficiency and explore a viable solution to the prevalent waste of renewable energy in power systems.

The cycle efficiency is a key indicator of RCAES system and can be significantly impacted by the key parameters of the system. Different kind of efficiency definitions are compared in [14] and the thermodynamic effect of advanced adiabatic compressed air energy storage system is analyzed in [15]. However, neither the efficiency evaluation method nor the impact of the parameters is concerned by any of the aforementioned references.

Based on the electric-mechanic-thermal dynamic process and measurable parameters of RCAES system, we proposed an efficiency evaluation method of RCAES system in [16] previously. One advantage of the proposed method is that it can be extended to study the impact of key parameters on the cycle efficiency of RCAES system, which is to be fulfilled in this paper. The key parameters of a RCAES system in this paper includes compression ratio, exhaust air pressure of throttle (EAPT) and the maximum working pressure (MWP) of compressed air storage vessel (CASV).

The remaining of this paper is organized as follows. Firstly, the efficiency evaluation method proposed in [16] will be briefly reviewed and the analytical method will also be formulated theoretically. Then the typical design scheme of RCAES project is studied. Finally, the conclusions are drawn.

2 Efficiency evaluation of RCAES system

2.1 Main assumptions

A simplified structure of RCAES system is showed in Fig. 1 including four main parts: compression, thermal energy storage (TES), CASV and expansion. The main assumptions in the system are as follow:

- 1) Ideal gas during the operation;
- 2) The air mass flow rate in compression and expansion process is known and constant in operation;
- 3) The isothermal model is adopted for CASV in which the temperature is the same as ambient circumstances;
- 4) The temperature and pressure of compressed air after throttling become constant.

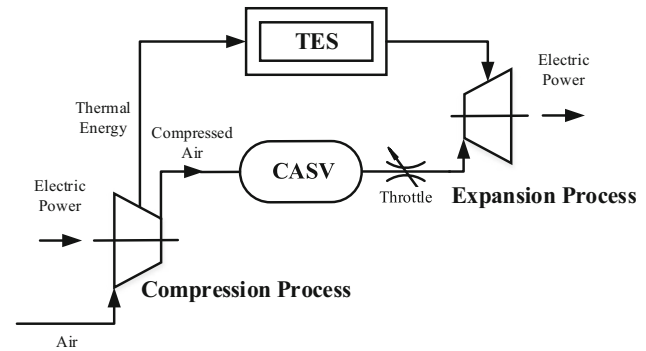


Fig. 1 Design structure of RCAES system

To facilitate the energy conversion process, without loss of generality, we further assume that:

1) The compression process starts when the pressure of CASV reaching its minimum value p_{str}^{\min} and ends when the pressure reaching its maximum value p_{str}^{\max} . Besides, EAPT denoted by p_{eap} is equal to p_{str}^{\min} .

2) The compressor consists of N stages of which stage 1 to stage $N - 1$ are steady stages and the last stage, i.e. stage N is an unsteady stage. The exhaust air pressure of stage $N - 1$ denoted by $p_{\text{cou},N-1}$, is lower than the MWP of CASV, i.e. $p_{\text{str}}^{\min} < p_{\text{cou},N-1} < p_{\text{str}}^{\max}$, while the exhaust air pressure of the last stage denoted by $p_{\text{cou},N}$ is larger than the MWP of CASV, i.e. $p_{\text{cou},N} > p_{\text{str}}^{\max}$.

Hence, all the stages of compressor will work simultaneously and the previous $N - 1$ stages are steady while the last stage is unsteady with time-variant pressure with the same value as CASV. Once the above assumptions are not satisfied for a practical RCAES system, the compression process can be formulated in a multi-period way with the same methodology. Furthermore, TES can be controlled to keep the inlet air temperature of all compression stages the same value except the 1st one in practical engineering and the corresponding temperature is denoted by T_{cin} in this paper.

2.2 Efficiency formulation of the whole RCAES system

Traditional and general efficiency evaluation method for CAES system is indicated by the ratio of the output electric energy and input electric energy. However, this method is merely applicable to systems already in operation and can hardly be extended to analyze or optimize the key parameters of the system. To overcome the deficiency, we proposed an efficiency evaluation method based on the energy conversion of compression and expansion process in [16].

2.2.1 Energy conversion in compression process

In compression process, the RCAES system is charged with electric power of which one part is stored in high-pressure air as molecular potential energy and the other part is stored in high-temperature water as thermal energy. However, the close relationship between electric power and compression work can be illustrated with the compression efficiency η_{com} . The compression efficiency is defined as the ratio of compression work and electric power charged in the compression process and is regarded as a known parameter when the system efficiency is analyzed in this paper.

As the isothermal model is adopted for CASV, the operation time (denoted as t_{com} with the unit of s) of the compression process can be illustrated as a function of p_{str} based on the state equation of ideal gas under normal circumstances which is expressed as follows:

$$t_{\text{com}} = \frac{V_{\text{str}}(p_{\text{str}} - p_{\text{str}}^{\min})}{q_{\text{com}} R_g T_{\text{str}}} \quad (1)$$

where p_{str} , V_{str} , T_{str} are pressure, volume and temperature of CASV with units of Pa, m^3 , K separately; q_{com} is the exhaust air rate of compressor with unit of kg/s ; $R_g = 287.1 \text{ J}/(\text{kg} \cdot \text{K})$ is a gas constant of air under normal circumstances [17].

When the p_{str} reaches the MWP of CASV, the value of t_{com} equals the operation time of compression process.

In the compression process, the compression work of steady stages and unsteady stage should be calculated separately as the compression power of unsteady stage changes dynamically in accordance with the pressure of CASV.

The total compression power (denoted by P_{std} with the unit of kW) of steady stages $1 \sim N - 1$ remain unchanged and can be expressed as follows [18]:

$$P_{\text{std}} = \frac{q_{\text{com}} R_g \gamma}{10^3 \times (\gamma - 1)} \left(\lambda^{\frac{\gamma-1}{\gamma}} - 1 \right) [T_{\text{c1}} + (N - 2) T_{\text{cin}}] \quad (2)$$

where λ is the ratio of each stage of compressor satisfying $\lambda > 1$; T_{c1} is the inlet temperature of the 1st stage and γ is the polytropicexponent of each stage.

The total compression work (denoted by W_{std} with the unit of kWh) of steady stages can then be illustrated as follows after the multiplication of (1) and (2):

$$\begin{aligned} W_{\text{std}}(p_{\text{str}}) &= P_{\text{std}} t_{\text{com}} / 3600 \\ &= \frac{V_{\text{str}} \gamma (p_{\text{str}} - p_{\text{str}}^{\min}) (\lambda^{\frac{\gamma-1}{\gamma}} - 1)}{3.6 \times 10^5 T_{\text{str}} (\gamma - 1)} [T_{\text{c1}} + (N - 2) T_{\text{cin}}] \end{aligned} \quad (3)$$

Similarly, the last stage of compressor is unsteady of which the exhaust air pressure is the same with CASV. The

compression power (denoted by $P_{\text{utd}}(p_{\text{str}})$ with the unit of kW) can be expressed as [18]:

$$P_{\text{utd}}(p_{\text{str}}) = \frac{q_{\text{com}} R_g T_{\text{cin}} \gamma}{10^3 (\gamma - 1)} \left[\left(\frac{p_{\text{str}}}{p_{\text{cin},N}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (4)$$

where $p_{\text{cin},N}$ is the inlet pressure of stage N .

Then, the compression work (denoted by $W_{\text{utd}}(p_{\text{str}})$ with the unit of kWh) can be obtained after integrating the compression power on time basis.

$$\begin{aligned} W_{\text{utd}}(p_{\text{str}}) &= \int \frac{P_{\text{utd}}}{3600} dt = \int \frac{V_{\text{str}} P_{\text{utd}} / 3600}{q_{\text{com}} T_{\text{str}} R_g} dp \\ &= \alpha_1 \left[\left(\frac{p_{\text{str}}}{p_{\text{cin},N}} \right)^{\frac{2\gamma-1}{\gamma}} - \left(\frac{p_{\text{str}}^{\min}}{p_{\text{cin},N}} \right)^{\frac{2\gamma-1}{\gamma}} \right] - \alpha_2 (p_{\text{str}} - p_{\text{str}}^{\min}) \end{aligned} \quad (5)$$

where $\alpha_1 = \frac{T_{\text{cin}} V_{\text{str}} \gamma^2 \lambda^{N-1} p_{\text{cin},1}}{3.6 \times 10^{-5} T_{\text{str}} (2\gamma-1)(\gamma-1)}$, $\alpha_2 = \frac{T_{\text{cin}} V_{\text{str}} \gamma}{3.6 \times 10^{-5} T_{\text{str}} (\gamma-1)}$.

In summary, the compression power and work can be expressed as a function of p_{str} :

$$P_{\text{com}}(p_{\text{str}}) = P_{\text{std}} + P_{\text{utd}}(p_{\text{str}})$$

$$W_{\text{com}}(p_{\text{str}}) = W_{\text{std}}(p_{\text{str}}) + W_{\text{utd}}(p_{\text{str}}) \quad (6)$$

In (6), P_{std} denotes the total compression power of steady stages which is independent of p_{str} and $P_{\text{utd}}(p_{\text{str}})$ denotes the compression power of unsteady stage changing along with p_{str} . The total compression power $P_{\text{com}}(p_{\text{str}})$ in the compression process is a summation of compression powers of steady and unsteady stages and thus a function of p_{str} . The total compression work $W_{\text{com}}(p_{\text{str}})$ can be explained similarly.

Then, the electric energy (denoted by $E_{\text{com}}^{\text{max}}$ with the unit of kWh) charged during the compression process can be expressed as:

$$E_{\text{com}}^{\text{max}} = \frac{W_{\text{com}}(p_{\text{str}}^{\text{max}})}{\eta_{\text{com}}} \quad (7)$$

2.2.2 Energy conversion in expansion process

In the expansion process, the high-pressure air changes into constant-temperature and isopiestic air after throttling, and then drives the turbine to generate electric power after exchanging heat with TES system. Similar to the compression process, the relationship of expansion work and electric energy can be illustrated by the expansion efficiency η_{tur} which is defined as the ration of discharged electric power and the expansion work in this paper. The expansion efficiency is also regarded as a known parameter when analyzing the system efficiency in this paper.

Due to the throttling effect, all stages are steady in expansion process. Supposing the tempreture of inlet air and polytropicexponent are indicated by T_{tin} and μ

separately, the total expansion power (denoted by P_{tur} with the unit of kW) can be expressed as follows [18]:

$$P_{\text{tur}} = -\frac{Mq_{\text{tur}}R_gT_{\text{tin}}}{10^3(\mu-1)}(\phi^{\frac{\mu-1}{\mu}} - 1) \quad (8)$$

where M is the total number of stage in the turbine; ϕ is the expansion ratio of each stage satisfying $\phi < 1$; q_{tur} is the exhaust air rate of turbine with the unit of kg/s.

The expansion time (denoted as t_{tur} with the unit of s) can be obtained in the same way as described in 2.2.1 showed as follows:

$$t_{\text{tur}} = \frac{(p_{\text{str}}^{\text{max}} - p_{\text{str}})V_{\text{str}}}{q_{\text{tur}}R_gT_{\text{str}}} \quad (9)$$

Hence, the expansion work (denoted by W_{tur} with the unit of kWh) can be expressed as a function of p_{str} and showed as follows:

$$\begin{aligned} W_{\text{tur}}(p_{\text{str}}) &= P_{\text{tur}}t_{\text{tur}}/3600 \\ &= \frac{MT_{\text{tin}}\mu V_{\text{str}}(p_{\text{str}}^{\text{max}} - p_{\text{str}})}{3.6 \times 10^5 T_{\text{str}}(\mu-1)}(1 - \phi^{\frac{\mu-1}{\mu}}) \end{aligned} \quad (10)$$

The electric energy (denoted by $E_{\text{tur}}^{\text{max}}$ with the unit of kWh) discharged by the RCAES system can then be expressed as the multiplication of expansion work and expansion efficiency:

$$E_{\text{tur}}^{\text{max}} = W_{\text{tur}}(p_{\text{str}})\eta_{\text{tur}} \quad (11)$$

Finally, the efficiency of RCAES system can be calculated as (12) and the details can be found in Appendix A.

$$\eta_{\text{RCAES}} = \frac{E_{\text{tur}}^{\text{max}}}{E_{\text{com}}^{\text{max}}} = \frac{W_{\text{tur}}(p_{\text{str}}^{\text{min}})}{W_{\text{com}}(p_{\text{str}}^{\text{max}})}\eta_{\text{com}}\eta_{\text{tur}} \quad (12)$$

According to the above formulas, the efficiency of the RCAES system is a nonlinear function of λ , p_{cap} and $p_{\text{str}}^{\text{max}}$.

2.3 The impact of key parameters on the efficiency of RCAES systems

2.3.1 The impact of compression ratio λ

When the compression ratio increases, more electric energy will be charged into the RCAES system and more thermal energy will be released by the compressor and absorbed by the TES system in compression process. Consequently, more thermal energy will be reused by the turbine and more electric energy will be discharged in the expansion process.

The relationship between the inlet air temperature of compressor T_{cin} and the exhaust air temperature in steady state, denoted by T_{cou} , can be showed as follows:

$$T_{\text{cou}} = T_{\text{cin}}\lambda^{\frac{\gamma-1}{\gamma}} \quad (13)$$

To establish the relationship of T_{cou} and the inlet air temperature of the turbine T_{tin} , a reasonable and applicable technique in engineering is assuming the gap being a constant, indicated by ΔT , which represents the efficacy of the TES. The smaller the value of ΔT is, the better the efficacy of the TES is. Therefore, the relationship of T_{cou} and T_{tin} can be expressed as follows:

$$T_{\text{tin}} = T_{\text{cou}}\lambda^{\frac{\gamma-1}{\gamma}} + \Delta T \quad (14)$$

By substituting (14) into (12), we can get the mathematical expression of the efficiency of RCAES system (see Appendix).

Additionally, to ensure all of the compressor working properly, the exhaust pressure of the stage $N-1$ should be no more than the MWP of CASV showed as follows:

$$p_{\text{cin},1}\lambda^{N-1} < p_{\text{str}}^{\text{max}}$$

Otherwise the last stage, i.e. stage N will be useless. Similarly, stage N of the compressor should be larger than the MWP of CASV showed as follows implying that the maximum pressure of CASV can only be reached when all stages work simultaneously.

$$p_{\text{cin},1}\lambda^N > p_{\text{str}}^{\text{max}}$$

Therefore, the compression ratio λ should satisfy

$$\sqrt[N]{\frac{p_{\text{str}}^{\text{max}}}{p_{\text{cin},1}}} < \lambda < \sqrt[N-1]{\frac{p_{\text{str}}^{\text{max}}}{p_{\text{cin},1}}} \quad (15)$$

2.3.2 The impact of EAPT p_{cap}

On one hand, the variety of EAPT will affect the operation time of both compression and expansion process according to (1) where $p_{\text{str}}^{\text{min}} = p_{\text{cap}}$ under given assumptions. On the other hand, as the exhaust air pressure of the turbine's last stage $p_{\text{tou},M}$ and total stage number of the turbine M are both fixed, the relationship of the expansion ratio ϕ can be expressed as

$$\phi = \sqrt[M]{\frac{p_{\text{tou},M}}{p_{\text{cap}}}} \quad (16)$$

In the above formulation, the reason that $p_{\text{tou},M}$ can be treated as a constant is that the exhaust air pressure of the last stage of turbine and the air pressure of ambient circumstances are approximately equal in the practical engineering applications.

By substituting (16) into (12), we can get the expression of the efficiency of RCAES system over p_{cap} (see Appendix).



2.3.3 The impact of the MWP of CASV $p_{\text{str}}^{\text{max}}$

Similar to the impact of EAPT, the MWP of CASV will affect the efficiency of RCAES system indirectly. As the system efficiency is a nonlinear function of $p_{\text{str}}^{\text{max}}$, the specific impact will be analyzed in case study.

Additionally, $p_{\text{str}}^{\text{max}}$ also should satisfy the following constraint to guarantee the efficacy of every stage of the compressor, i.e., the MWP of CASV can be reached only when all stages work simultaneously.

$$p_{\text{cin},1} \lambda^{N-1} < p_{\text{str}}^{\text{max}} < p_{\text{cin},1} \lambda^N \quad (17)$$

3 Case study

3.1 System introduction

The typical design scheme of the RCAES project showed in Fig. 2. According to Fig. 2, the compressor consists of 5 stages and the turbine consists of 3 stages. The basic parameters are showed in Table 1 under the comprehensive consideration of the operation performance and construction cost of the RCAES system.

3.2 Efficiency of RCAES system with basic parameters

According to (1), the compression process can be divided into two periods. The first one takes 3.65 h and the

Table 1 Parameters of practical RCAES system

Parameter	Value	Parameter	Value
T_{c1}	25 °C	$p_{\text{str}}^{\text{min}} (p_{\text{eap}})$	2.5 MPa
$p_{\text{cin},1}$	0.1 MPa	$p_{\text{str}}^{\text{max}}$	10 MPa
η_{com}	75 %	λ	3
η_{tur}	75 %	ϕ	1/3
T_{str}	20 °C	q_{com}	0.46 kg/s
ΔT	40 °C	q_{tur}	2.41 kg/s
γ	1.4	μ	1.4
$p_{\text{tou},\text{M}}$	0.11 MPa	V_{str}	100 m ³
T_{cin}	86.35 °C		

second one takes 1.36 h. The operation time of the expansion process is 1.14 h according to (9). Fig. 3 and Fig. 4 show the compression power/energy process changing with p_{str} in the compression process.

As showed in Fig. 3 and Fig. 4, the working pressure of CASV p_{str} increases over compression power P_{com} and compression work W_{com} nonlinearly. In the compression process, the maximum electric power and electric energy charged into the RCAES system is 283.90 kW and 1407.55 kW separately. The electric power discharged by the RCAES system remains 498.17 kWh and the maximum electric energy discharged is 567.92 kW. According to (12), the efficiency of RCAES system is 40.35 % in the given case.

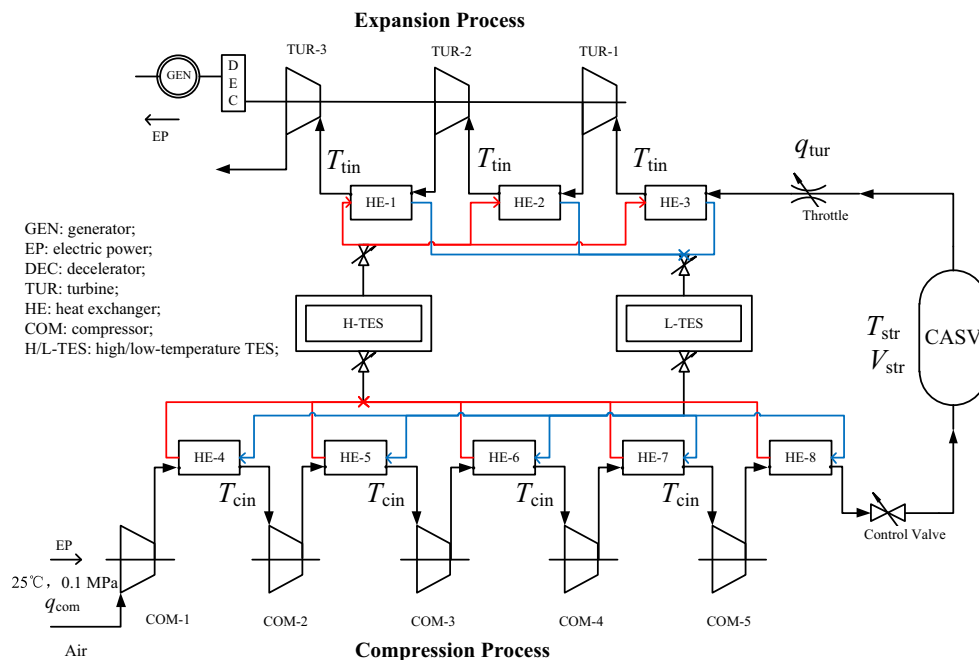


Fig. 2 Design scheme of RCAES project

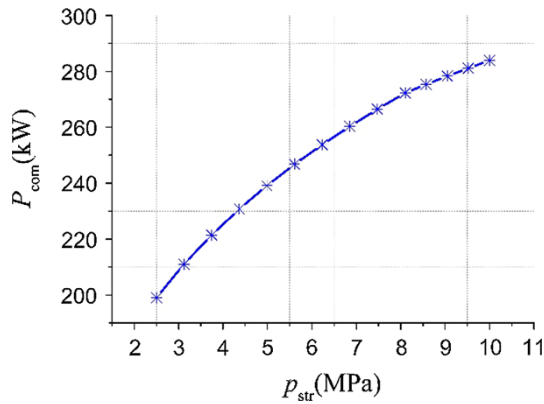


Fig. 3 Compression power P_{com} with different p_{str} in compression process

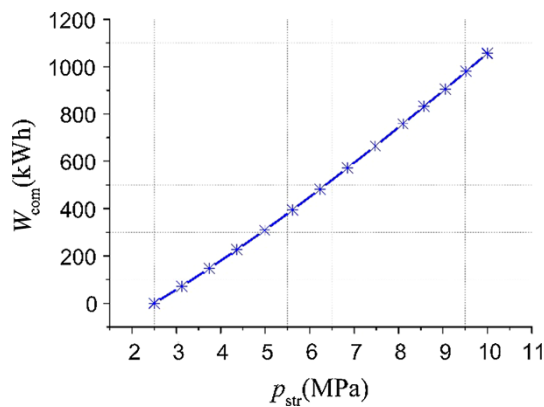


Fig. 4 Compression work W_{com} with different p_{str} in compression process

3.3 The impact of compression ratio

In the formulation of this part, all parameters excluding the compression ratio λ of the RCAES system are given as basic parameters given in Table 1 and λ must satisfy the following condition according to (15).

$$2.5119 \approx \sqrt[N]{\frac{p_{str}^{\max}}{p_{cin,1}}} < \lambda < \sqrt[N-1]{\frac{p_{str}^{\max}}{p_{cin,1}}} \approx 3.1623$$

Thus, λ will be fixed as the following given values successively:

$$\lambda = 2.6, 2.7, 2.8, 2.9, 3.0, 3.1$$

The electric energy charged in compression process and discharged in expansion process with different λ are given in Fig. 5 and Fig. 6 and both of them are monotonically increasing with λ . The efficiency of RCAES system, i.e., the ratio of E_{tur}^{\max} and E_{com}^{\max} is given in Fig. 7.

As showed in Fig. 7, the RCAES system's efficiency increases approximately linearly over λ . This is partly

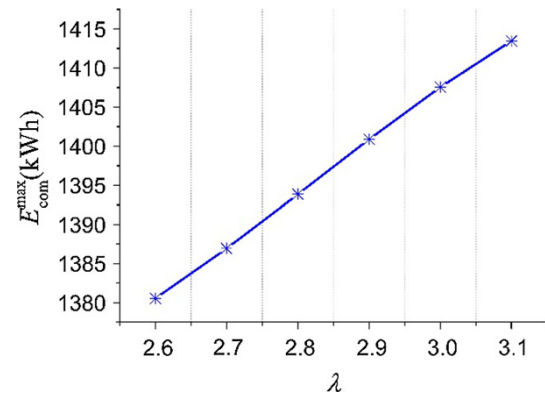


Fig. 5 Electric energy exchanged with different λ in compression processes

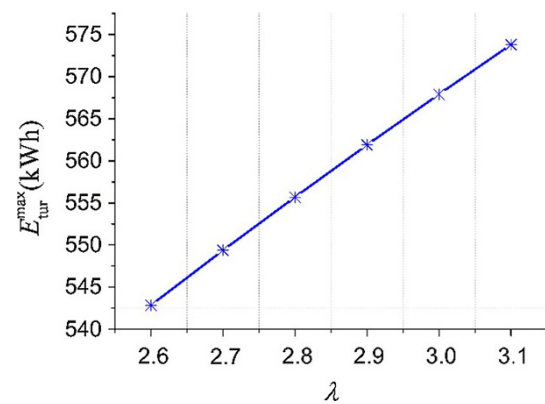


Fig. 6 Electric energy exchanged with different λ in expansion processes

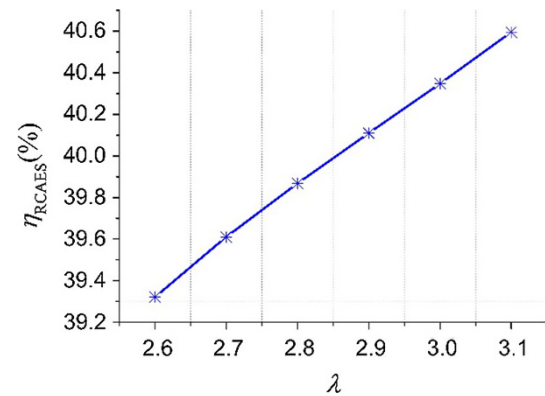


Fig. 7 Efficiency of RCAES system with different λ

because of the narrow feasible region of λ under the given design scheme, although the nonlinearity is indicated by the formulas in Appendix.

As the compression ratio λ increases, more thermal energy is released, resultantly, raising the temperature of H-TES. Accordingly, the rising inlet air temperature of the turbine implies that more electric energy will be discharged in the expansion process. The simulation result shows that

the incremental electric energy discharged in expansion process is larger than the incremental electric energy charged in compression process as λ increases, i.e., the efficiency of the RCAES system is increased.

3.4 The impact of EAPT

Although p_{eap} can be arbitrary value in the range of 0.1 MPa ~ 10 MPa theoretically, p_{eap} will be fixed as the following given values successively in our formulation:

$$p_{\text{eap}} = 2.5 \text{ Mpa}, 3 \text{ Mpa}, 3.5 \text{ Mpa}, \dots, 6.5 \text{ Mpa}, 7 \text{ Mpa}$$

The simulation result is showed in Fig. 8 and Fig. 9, in which $E_{\text{com}}^{\text{max}}$ and $E_{\text{tur}}^{\text{max}}$ decrease over p_{eap} linearly and nonlinearly separately. As the change rate of $E_{\text{tur}}^{\text{max}}$ is smaller than $E_{\text{com}}^{\text{max}}$, the efficiency of the system increases nonlinearly and there is less energy loss with bigger value of p_{eap} , which is consistent with the simulation result in Fig. 10.

The energy charged into RCAES system is stored in TES as high-temperature water and in CASV as high-pressure air. Given the volume of the CASV system, more

energy will be stored with higher pressure. However, the high-pressure air becomes isothermal and isopiestic after throttling resulting in the decrement of compressed air's capability of doing work. Furthermore, more energy loss will be caused with larger difference of the pressure.

3.5 The impact of the MWP of CASV

According to (17), $p_{\text{str}}^{\text{max}}$ must satisfy the following condition:

$$8.1 \text{ MPa} = p_{\text{cin},1} \lambda^{N-1} < p_{\text{str}}^{\text{max}} < p_{\text{cin},1} \lambda^N = 24.3 \text{ MPa}$$

Thus, $p_{\text{str}}^{\text{max}}$ will be fixed as the following given values successively:

$$p_{\text{str}}^{\text{max}} = 10 \text{ MPa}, 12 \text{ MPa}, \dots, 22 \text{ MPa}, 24 \text{ MPa}$$

Fig. 11 and Fig. 12 show that the electric energy charged in compression process and discharged in expansion process increases approximately linearly over $p_{\text{str}}^{\text{max}}$. This results in nonlinear decrease of the efficiency of the system which is showed in Fig. 13.

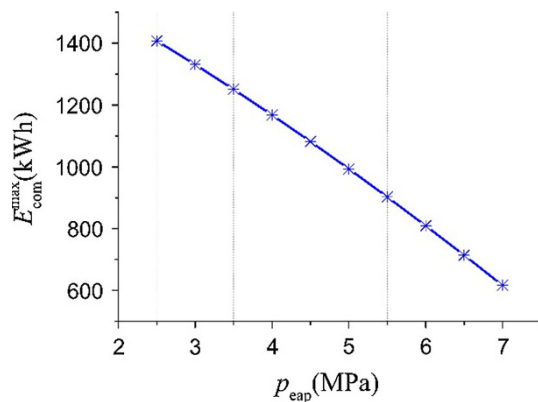


Fig. 8 Electric energy exchanged with different p_{eap} in the compression process

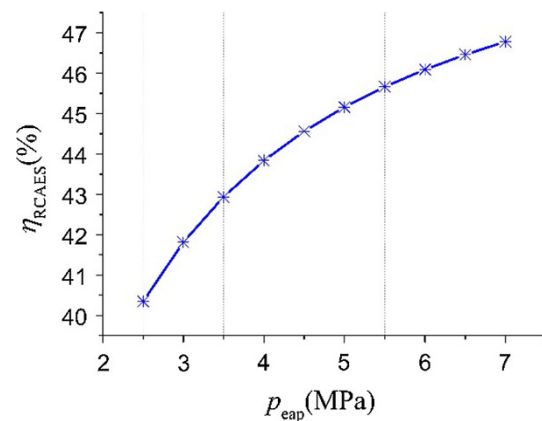


Fig. 10 Efficiency of RCAES system with different p_{eap}

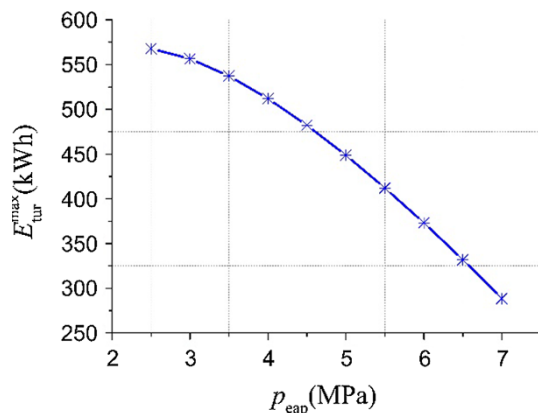


Fig. 9 Electric energy exchanged with different p_{eap} in the expansion process

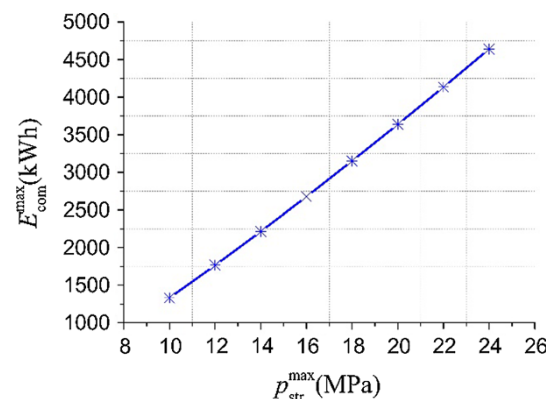


Fig. 11 Electric energy exchanged with different $p_{\text{str}}^{\text{max}}$ in the compression process

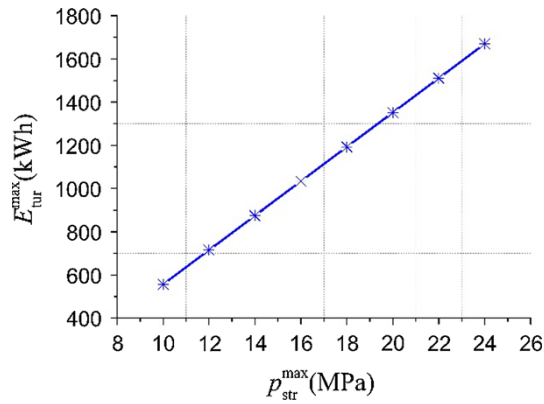


Fig. 12 Electric energy exchanged with different p_{str}^{max} in the expansion process

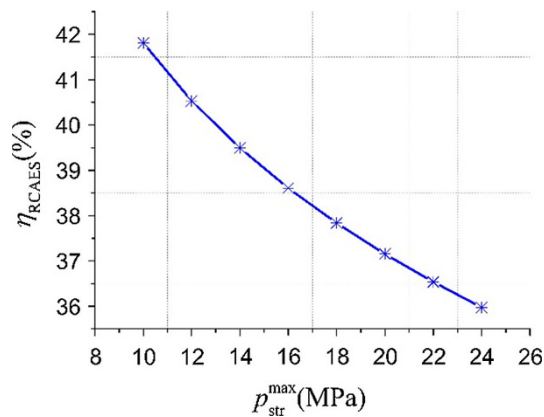


Fig. 13 Efficiency of RCAES system with different p_{str}^{max}

If p_{eap} is fixed, the compressed air's capability of doing work will decrease after throttling which results in lower efficiency of the RCAES system. The simulation result also indicates that the loss is larger when MWP of the CASV is higher.

According to all of the above simulation results, higher compression ratio, higher EAPT and lower MWP of CASV in certain range are helpful to improve the cycle efficiency of the RCAES system.

4 Conclusions

The RCAES system is widely concerned in recent years. Based on the efficiency evaluation method, the impacts of key parameters including compression ratio, EAPT and the MWP of CASV on the cycle efficiency of RCAES system are studied in this paper. The simulation results reveal the variation of the system efficiency over these parameters. This paper provides useful information to design the

RCAES system. In addition, other key indicators of the RCAES system, e.g. maximum electric power, operation hour, maximum capacity should also be considered in practical engineering applications. The efficiency evaluation model proposed in this paper can also be used to study these influencing factors.

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Appendix

According to part 2.2, the efficiency of RCAES system can be obtained by substituting (3), (5) and (10) into (12):

$$\eta_{RCAES} = \frac{c_1 z_1}{c_2 z_2 + c_3 z_3 - c_4 z_1}$$

where

$$c_1 = \frac{MT_{in}\mu}{(\mu-1)} \left(1 - \phi^{\frac{\mu-1}{\mu}}\right); c_2 = \frac{\gamma[T_{c1} + (N-2)T_{cin}]}{(\gamma-1)}$$

$$c_3 = \frac{T_{cin}\gamma^2 p_{cin,1}}{(2\gamma-1)(\gamma-1)}; c_4 = \frac{T_{cin}\gamma}{(\gamma-1)}$$

$$z_1 = p_{str}^{max} - p_{str}^{min}; z_2 = \left(\lambda^{\frac{\gamma-1}{\gamma}} - 1\right)(p_{str}^{max} - p_{str}^{min})$$

$$z_3 = \lambda^{N-1} \left[\left(\frac{p_{str}^{max}}{\lambda^{N-1} p_{cin,1}} \right)^{\frac{2\gamma-1}{\gamma}} - \left(\frac{p_{str}^{min}}{\lambda^{N-2} p_{cin,1}} \right)^{\frac{2\gamma-1}{\gamma}} \right]$$

According to part 2.3.1, the efficiency of the RCAES system over λ can be obtained by replacing T_{in} in c_1 with (14):

$$\eta_{RCAES} = \frac{c'_1 z_1}{c_2 z_2 + c_3 z_3 - c_4 z_1}$$

where $c'_1 = \frac{M(T_{cin}\lambda^{\frac{\gamma-1}{\gamma}} + \Delta T)\mu}{(\mu-1)} \left(1 - \phi^{\frac{\mu-1}{\mu}}\right)$, $c_2 \sim c_4$ and $z_1 \sim z_3$ remain unchanged.

According to part 2.3.2, replace ϕ in c_1 with (16), the efficiency of the RCAES system over p_{eap} can be obtained as follows:

$$\eta_{RCAES} = \frac{c''_1 z_1}{c_2 z_2 + c_3 z_3 - c_4 z_1}$$

where, $c''_1 = \frac{M(T_{cin}\lambda^{\frac{\gamma-1}{\gamma}} + \Delta T)\mu}{(\mu-1)} \left(1 - \left(\sqrt[\mu]{\frac{p_{tou,M}}{p_{cap}}}\right)^{\frac{\mu-1}{\mu}}\right)$, $c_2 \sim c_4$ and $z_1 \sim z_3$ remain unchanged.



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